Effects of Industrial Heat Treatment on the Properties of Spruce and Pine Woods

Bilgin Icel,* Gurcan Guler, Onur Isleyen, Abdullah Beram, and Muhammed Mutlubas

The purpose of this study was to evaluate the effects of an industrial heat treatment (ThermoWood) based on changes in the strength properties, density, and color of spruce (*Picea abies*) and pine (*Pinus sylvestris*) woods. Samples were subjected to heat treatment processes at 212 °C for a duration of 120 min. The results showed that the applied process caused a 2.56 to 6.12% decrease in density. Dimensional stability was considerably improved, with ASE values of 58% and 52% for spruce and pine, respectively. The color became darker after treatment. The process caused a significant ($p<0.05$) reduction (8 to 42%) for all investigated mechanical properties at a specific moisture level (12%). However, the mechanical properties of wood are closely related to its moisture content, and heat-treated wood is less hygroscopic than untreated wood. It was found that, after long-term acclimatization, heat-treated samples had almost half the equilibrium moisture content of control samples. Because the changes that occurred after this heat treatment are irreversible, it is possible that ThermoWood has lower equilibrium moisture content than untreated wood. Therefore, this should be taken into account when investigating the mechanical design values of heat-treated wood.

Keywords: Industrial Heat treatment; Spruce; Pine; Wood; ThermoWood

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INTRODUCTION

Wood, as a renewable and sustainable natural resource, has been used in both indoor and outdoor applications over the years. As a biological material, instability under changing moisture conditions and biodegradability are significant disadvantages of the material. Therefore, many researchers have focused on this topic, and different techniques have been developed. Heat treatment is one of the wood modification methods applied to improve the dimensional stability and durability of the material (Boonstra *et al.* 2006; Kortelainen *et al.* 2006; Esteves and Pereira 2009). Different thermal modification methods have been developed in France, Finland, the Netherlands, and Germany since the middle of the last century (Kortelainen *et al.* 2006). Because there is no chemical application during the process, heat-treating wood is generally considered an eco-friendly method (Rapp 2001; Anonymous 2003). The modification of wood by heat treatment and its history and methods were reviewed very capably by Esteves and Pereira (2009). As a consequence of chemical changes in wood's structure that occur during the heat treatment process, the properties of wood are changed. Because of the variations in different heat treatment processes such as industrial-scale, semi-industrial-scale, and laboratory experiments, the properties of heat-treated wood vary greatly. The extent of change in wood properties with heat treatment mainly depends on the heat treatment method, the

tree species and its wood's characteristics, the initial moisture content of the wood, the surrounding atmosphere, the treatment temperature, and the time duration. Temperature has greater influence on many wood properties than time (Mitchell 1988; Rapp 2001; Hill 2006; Esteves and Pereira 2009; Guller 2012).

The known gains resulting from industrial heat-treatment are increased biological durability and decreased shrinking and swelling of the wood (Viitaniemi 1997a,b; Jamsa *et al.* 2000; Kamdem *et al.* 2002; Hakkou *et al.* 2005; Repellin and Guyonnet 2005; Sahin Kol 2010) as well as lower equilibrium moisture content, increased thermal insulation (Viitaniemi 2000; Anonymous 2003; Esteves *et al.* 2008; Akyildiz and Ates 2008; Poncsac *et al.* 2011), and darkened color (Anonymous 2003; Mitsui *et al.* 2003; Bekhta and Niemz 2003). Therefore, a broadening range of heat-treated softwood and temperate hardwood products have been supplied as alternatives to tropical hardwood in the market. However, the attained color is not stable against light exposure (Mitsui *et al.* 2003) and no known cost-effective and easy method has been found to prevent this fading (Kaygin *et al.* 2009). These are the favorable results of heat treatment. On the other hand, as a result of thermal degradation, wood loses its weight, becomes more brittle, and its mechanical properties decrease in relation to the severity of the heat treatment (Santos 2000; Rapp and Sailer 2000; Bekhta and Niemz 2003; Hakkou *et al.* 2005).

Although thermal wood modification is a long-known technology, it has received increased attention in the last decade, particularly in Europe, leading to intensified industrial production and commercialization (Arnold 2010). There are 30 companies across Europe operating thermal treatment plants with a total capacity of about 300,000 m^3. The leaders of the market, with approximately 40% of this capacity, are in Finland, followed by Germany (13%), the Netherlands (12%), and Estonia (8%). The remaining capacity is distributed throughout France, Croatia, Austria, Switzerland, Sweden, and Turkey (Anonymous 2011).

ThermoWood (TW), the industrial-scale heat treatment process developed by the Technical Research Center of Finland (VTT), has been widening its place in the market. The wood is heated under low oxygen content (under 3.5%) with the presence of water steam. Low oxygen contents prevent the wood material from burning at high temperatures. Temperatures for the actual heat treatment period range from 150 °C to 240 °C and the duration times range from 0.5 h to 4 h (Viitaniemi 2000; Homan and Jorissen 2004).

The main purpose of this study was to determine the industrial heat treatment "ThermoWood" effects on the density, dimensional stability, and strength properties of wood, which are important properties for the outdoor usage of two important species in the market. Although the study focused on the effects of industrial-scale heat treatment on wood properties rather than laboratory conditions, the present results are compared with previously published literature dealing with industrial-scale heat treatment effects.

EXPERIMENTAL

Materials

The spruce (*Picea abies*) and pine (*Pinus sylvestris*) wood samples used for this study were obtained from an industrial plant. These species were chosen because of their increasing demand and importance in Turkish and European market. The lumber was stored and pre-dried at a lumber yard. The thermal treatment was carried out in the

industrial furnace of a forest product company following the industrial process (invented by Pentti Ek, Saila Jamsa, Hannu Viitanen, Pertti Viitaniemi and patented by VTT-EP0695408) trade name called as ThermoWood® (EU trademark number 000922765). Because the collaborating company has strict rules to keep the details of the process confidential, only the general information on the process is described briefly in the Introduction. Detailed information on ThermoWood and general mechanism of the process can be found in ThermoWood handbook (Anonymous 2003). The temperature used during the heat treatment period was 212 °C, and the duration time at this temperature was 120 min for softwood species (Thermo-D, for outdoor applications). The wood boards were sawn at similar size to the company applications for outdoor conditions (38x100x1500 mm), and test samples from sap wood were obtained. All of the wood boards were separated into two parts: part A was heat-treated, and part B was the control for each board (Fig. 1). To have real controls for the test samples, cutting plans were drawn on each part of the board before cutting (Fig. 1)

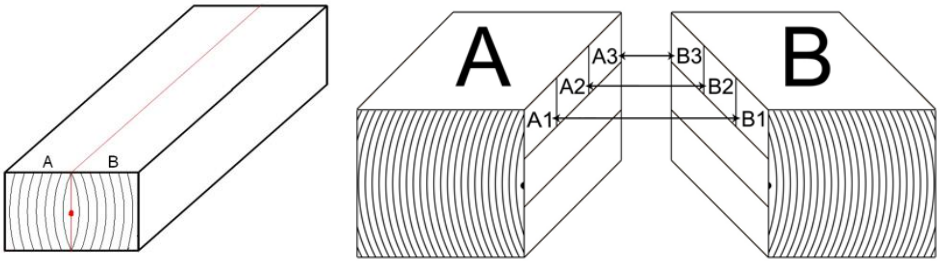

Fig. 1. Separation of the (A) treatment and (B) control parts of each wood board and cutting plans

Methods

The density of the samples was measured according to ISO standard (ISO/CD 13061-2 2014). Because of the fact that wood density is a highly variable property dependent on both species and location within the tree, the density was calculated in terms of percentage of decrease to evaluate treatment effects. The percentages of density decrease and mass loss were calculated relative to control samples.

The morphology of the wood samples was analyzed with a Tescan VEGA 2 LSU scanning electron microscope (SEM; Czech Republic) operating at an accelerating voltage of 15 kV and under high vacuum conditions.

Dimensional stability was determined by measuring the volumetric swelling percentage of the specimens immersed in a water bath at a controlled temperature of 20 °C. During the tests, the water in the water bath was re-circulated continuously to maintain the required temperature (20 °C) (Dubey 2010). Swelling measurements of the samples were measured with 0.01 mm accuracy at three different marked positions before and after immersion in water. Then, the specimens were weighed every 24 h; once the weight changes of the test specimens were less than 0.1%, it was assumed that the specimens had reached equilibrium. The weight was measured with an accuracy of ±0.001 g. The dimensions in the longitudinal, width (tangential), and thickness (radial) directions were measured to an accuracy of ±0.01 mm. The volumetric swelling coefficients (S) were determined using Eq. (1) (Rowell and Youngs 1981), given below,

$$S\,(\%) = \frac{V2 - V1}{V1} * 100 \quad (1)$$

where *V*2 is the wood volume after wetting with water and *V*1 is the wood volume of the oven-dried sample before wetting.

A variety of terms can be used to describe the degree of dimensional stability given to wood by treatments: antishrink efficiency, swelling percentage, dimensional stabilization efficiency, antiswelling efficiency, and percentage of reduction in swelling (*R*). The antiswelling efficiency (ASE), which was determined using Eq. (2) (Rowell and Youngs 1981), was used in the present work,

$$\text{ASE}\ (\%) = \frac{S2 - S1}{S1} * 100 \tag{2}$$

where *S*2 is the treated volumetric swelling coefficient and *S*1 is the untreated volumetric swelling coefficient.

Because wood is a hygroscopic material, most of its properties are considerably influenced by moisture content (MC). The mechanical properties, which are very important for the use of wood in structural applications, are known as the major influencing properties (Forest Products Laboratory 1999; Arnold 2010). Below the fiber saturation point (FSP), an increase in MC causes a decrease in mechanical properties, while above FSP, the effects of moisture are usually negligible. The various mechanical properties have different sensitivities to changes in MC, with strength properties being more sensitive than stiffness properties and static properties being more sensitive than dynamic properties (Dinwoodie 2000; Arnold 2010). All samples were conditioned in an automatic controlled conditioning room at 20 °C (±2 °C) and 65% (±5%) relative humidity. Assuming a similar type of conditioning and duration will result in different MC in treated and control samples, heat-treated samples were conditioned in two different durations: two months, which is the same duration for untreated samples that reached a 12% moisture content, and four months (to see MC difference for heat-treated samples for longer duration). Mechanical tests such as compression strength parallel to grain (CS//), modulus of rupture (MOR), and modulus of elasticity (MOE), were conducted in accordance with TS EN 408 (1997) (Turkish Standards; European Norm). A computerized universal testing machine was used for the tests. The MOR, MOE, and CS// were calculated with Eqs. (3), (4), and (5) (Bozkurt and Goker 1987; Dubey 2010),

$$\text{CS//} = \frac{\text{P}_{\max}}{\text{bh}} \tag{3}$$

$$MOR = \frac{3P_{\max} l}{2bh^2} \tag{4}$$

$$MOE = \frac{Pl^3}{4\Delta bh^3} \tag{5}$$

where P_{max} is the maximum load when the sample is broken, P is the load within the proportional deflection, Δ is the deflection at mid-length below the proportion deflection limit (mm), l is the supporting span (mm), b is the cross-sectional width of the test sample (mm), and h is the cross-sectional thickness of the test sample (mm).

After the mechanical tests, the MC of each sample was measured according to ISO 3130 (1975), and the moisture content of specimen in which moisture content

deviated from 12% was also determined. Heat-treated samples are generally known to have lower moisture contents than control ones. To equalize the moisture contents (12%) of the two groups (heat-treated and control samples conditioned for two months), the conversion Eq. (6) was used:

$$\text{(if } M_2 > \%12) \qquad \delta_{12} = \delta_m \left[1 + \alpha (M_2 - 12) \right]$$

$$\text{(if } M_2 < \%12) \qquad \delta_{12} = \delta_m \left[1 - \alpha (\left| M_2 - 12 \right|) \right] \tag{6}$$

where δ_{12} is the strength at a 12% moisture content (N/mm^2), δ_m is the strength at a moisture content deviated from 12% (N/mm^2), α is a constant showing the relationship between strength and moisture content (α = 0.05, 0.04, 0.02, for CS//, MOR, and MOE, respectively), and M_2 is the determined moisture content after tests (%) (Bozkurt and Goker 1987).

The color was measured from the tangential and radial surface of the wood specimens before and after heat treatment by a Konica Minolta Chroma-Meter CR-400 (Konica Minolta Corp.; Japan) colorimeter according to ISO 7724-2-3 (1984). The sensor head was 6 mm in diameter. Measurements were made using a D65 illuminant and a 10-degree Standard observer. Percentage of reflectance collected at 10-nm intervals over the visible spectrum (from 400 to 700 nm) was converted into the CIELAB color system, where L^* describes the lightness and a^* and b^* describe the chromatic coordinates on the green-red and blue-yellow axes, respectively. From the L^*, a^*, and b^* values, the difference in the lightness (ΔL^*) and chromaticity coordinates (Δa^* and Δb^*) were calculated using group mean values. The quantities ΔL^*, Δa^*, and Δb^* are the changes between pre- and post-treatment values. These values were used to calculate total color change (ΔE^*) according to Eq. (7) (ISO 7724/3 1984):

$$\Delta E_{ab}^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{7}$$

All statistical calculations were based on a 95% confidence level. An independent sample t-test was applied to compare control and treatment groups. DTREG (Standard Version 10.6.3, Phillip H. Sherrod, USA) was used for statistical analysis.

RESULTS AND DISCUSSION

Obtained results and descriptive statistics for density and strength properties are shown in Table 1. Compared with the control sample, wood density for the same moisture content (0% and 12%) decreased significantly ($p<0.05$) with heat treatment. Mass loss of heat-treated samples was found to be 5.8 % for pine and 7.6 % for spruce. These results are comparable with previously published reports for different species (Yildiz *et al.* 2006; Sevim Korkut and Guller 2008; Gunduz *et al.* 2009; Kaygin *et al.* 2009; Ghalehno and Nazerian 2011).

Because the circumstances of treatment differ among published works, the results were considered in terms of specific temperature and durations. For conditions of 190 °C and 180 min duration, a density decrease of about 3% for Scots pine was reported (Kortelainen *et al.* 2006), which is lower than current results (4 to 6%) for the same species but shorter duration (120 min) and higher temperature (212 °C). This result supports the idea that temperature has a greater influence on density loss than duration (Mitchell 1988; Rapp 2001; Hill 2006; Esteves *et al.* 2008). However, Akyildiz *et al.*

(2009) reported approximately 13% density loss (12.7 for oven-dry and 13.4 for air-dry density) for *P. nigra* heat-treated wood under 230 °C for 8 h. This means that in addition to high temperature, expanded durations also contribute to the mass loss of heat-treated wood. The depolymerization reactions of wood polymers are the main cause of the decrease in density. Above a certain temperature, the physical characteristics of hemicellulose (127 to 235 °C), lignin (167 to 217 °C), and cellulose (231 to 253 °C) change (Boonstra *et al.* 2007). Hemicellulose, which is less stable under the effects of heat than cellulose and lignin, plays an important role in the decreased physical properties of wood at high temperatures (Fengel and Wegener 1989; Hillis 1996). The decrease in density was found to be lower for spruce wood than for pine wood. This result can also be explained by the lower extractive content of spruce wood (Sehlstedt-Persson 2003).

Comparing control group heat treatments resulted in a significant ($p < 0.05$) reduction in swelling percentage of both species (Fig. 2). The antiswelling efficiency (ASE) values of spruce and pine were determined to be 58% and 52%, respectively. These values are similar to the findings of Rautkari *et al.* (2014) for heat-treated (120, 150, and 180 °C) Scots pine. Dimensional stability is an important property of wooden material, especially for usage under high humidity conditions. Thus, there have been many studies concerned with this topic. Reported results of wood stability reductions (%) vary from one study to another. These changes may be explained by differentiations in heat treatment methods, the standards that were followed, and the wood species. For example, ThermoWood heat treatment is carried out in the absence of oxygen. Many previous works were carried out in a laboratory-scale oven. The presence of air during heat treatment may lead to higher ASE and higher weight loss, and oxygen acts like a catalyst for changes in wood components during heating (Wang 2014). However, the general consensus is that heat-treated wood has a dimensional stability advantage compared with untreated wood (Hillis 1996; Viitaniemi 1997a; Akyildiz and Ates 2008; Sevim Korkut and Guller 2008; Korkut *et al.* 2008; Kaygin *et al.* 2009; Sahin Kol 2010; Karlsson *et al.* 2011; Aydemir *et al.* 2011; Poncsac *et al.* 2011).

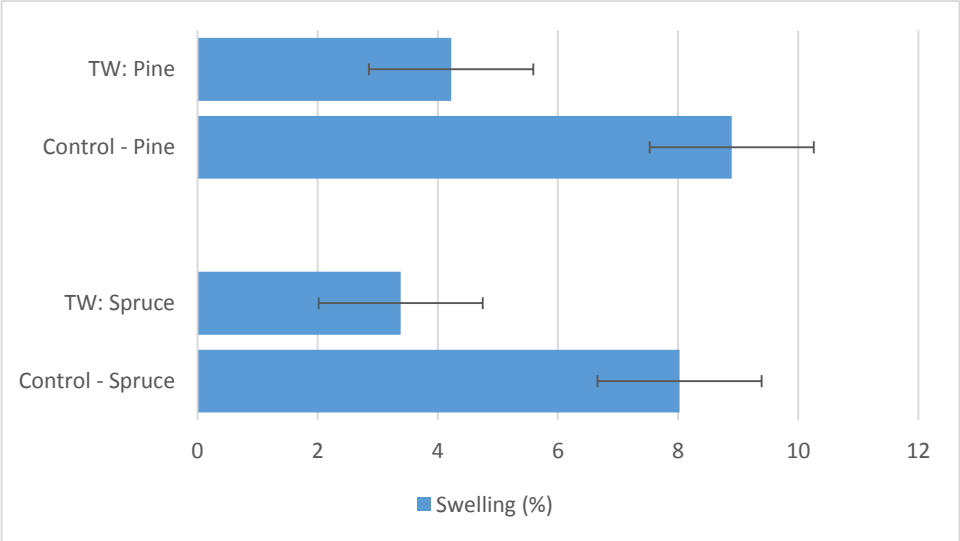

Fig. 2. Reductions in the volumetric swelling of groups after heat treatment

The availability and/or accessibility of the free hydroxyl groups of wood play an important role in water sorption (Boonstra and Tjeerdsma 2006). The degradation of cellulose causes a reduction in available free polar adsorption sites, including free hydroxyl groups for water (Burmester 1975; Hillis 1984; Feist and Sell 1987; Kartal *et al.* 2007; Aydemir *et al.* 2011). There was an increase in the relative proportion of the crystalline cellulose, where the hydroxyl groups are not easily accessible to water molecules (Pott 2004), and the cross-linking of the lignin network (Tjeerdsma *et al.* 1998), which might hinder the accessibility of free hydroxyl groups to water (Pizzi *et al.* 1994). Furthermore, at very high temperatures (over 200 °C), hemicellulose may be changed to less hygroscopic substances such as furfural polymers (Kamdem *et al.* 2002). Therefore, the decreased equilibrium moisture content (Gunduz *et al.* 2008), improved dimensional stability, and water repellency of heat-treated wood are mainly caused by the decomposition or transformation of hemicellulose at high temperatures. These are the most probable causes of the lower moisture contents of heat-treated samples after acclimatization in our study.

The hygroscopicity of heat-treated spruce wood was investigated by Borrega and Kärenlampi (2010) in relation to the mass loss that occurs during thermal treatment. They stated that the reduction in hygroscopicity is caused not only by mass loss, but by another mechanism exists as well. The hypothesis is that this mechanism is related to irreversible hydrogen bonding in the course of water movements within the pore system of the cell walls, and they suggest that intermediate relative humidity during a heat treatment would probably not result in reduced hygroscopicity if the relative humidity remained constant.

It is well-known that below the fiber saturation point (FSP), many strength properties of wood are affected by differences in moisture content (Kollmann and Côte 1968). The mechanical properties of wood are closely related to the moisture content of the timber. From this point of view, it is possible to think that heat treatment provides a positive contribution to the mechanical strength properties since heat-treated wood is less hygroscopic and the (maximum) amount of bound water is reduced (Boonstra *et al.* 2007). However, the ThermoWood process caused a significant ($p<0.05$) reduction (8 to 42%) for all investigated mechanical properties (Table 1). There is a general consensus in the literature that high-temperature heat treatments negatively affect wood's mechanical properties and that this can be explained by material losses in cell lumen and hemicellulose degradation due to applied high temperature (Rusche 1973; Esteves *et al.* 2008; Korkut 2008; Tasdemir and Hiziroglu 2014). Although reports on the effects of heat treatment on the anatomical structure of wood are very limited, it is possible that some anatomical changes in wood structure may also contribute to reductions in mechanical properties. For example, cracks between tracheids were noticed in treated softwood species by Boonstra *et al.* (2006). Softwood species with narrow annual rings and/or an abrupt transition from earlywood into latewood are sensitive to tangential cracks in the latewood section (although this depends on the wood species, process method, and conditions used). Radial cracks occur mainly in impermeable wood species such as Norway spruce, caused by large stresses in the wood structure during treatment. The sapwood of treated pine species reveals some damage to parenchyma cells in the rays and epithelial cells around resin canals (Boonstra 2008). Observations of anatomical features (more cracks) in the present work were in agreement with previous reports (*i.e.* Tasdemir and Hiziroglu 2014) on the SEM micrographs of heat-treated samples (Fig. 3). These features may contribute to abrupt fractures, which can lead to considerably different failure behavior of heat-treated wood, as observed in bending tests (Fig. 4).

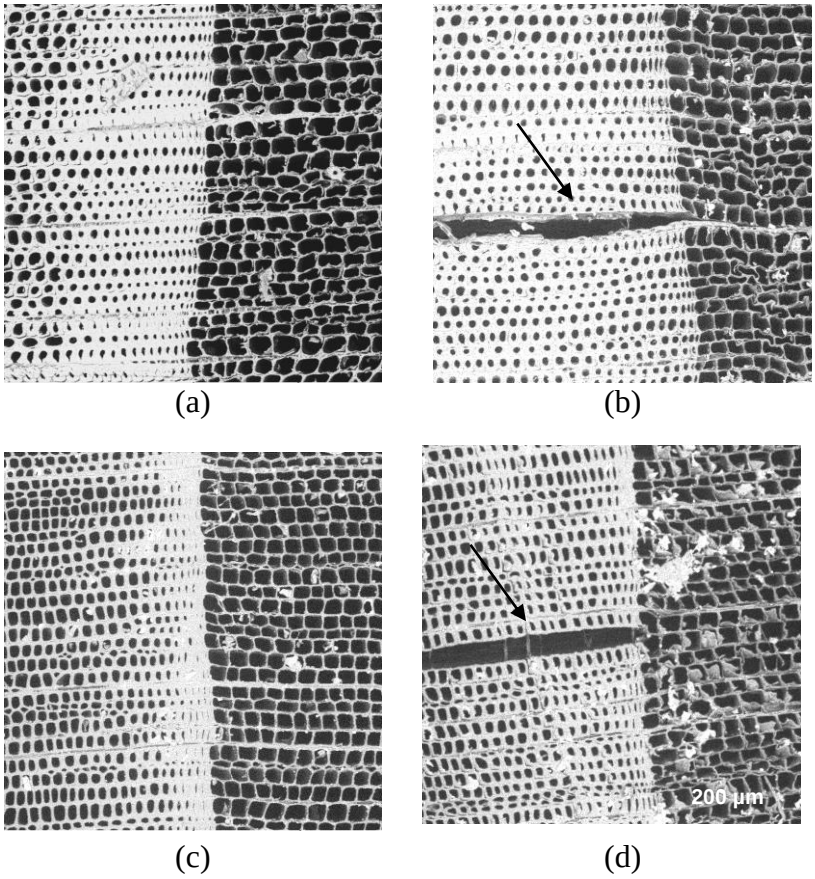

Fig. 3. SEM micrographs of heat-treated and control samples. The black arrows denote cracks. (a) Scotch pine sample for control (b) Scotch pine sample for heat treatment (c) Spruce sample for control (d) Spruce sample for heat treatment

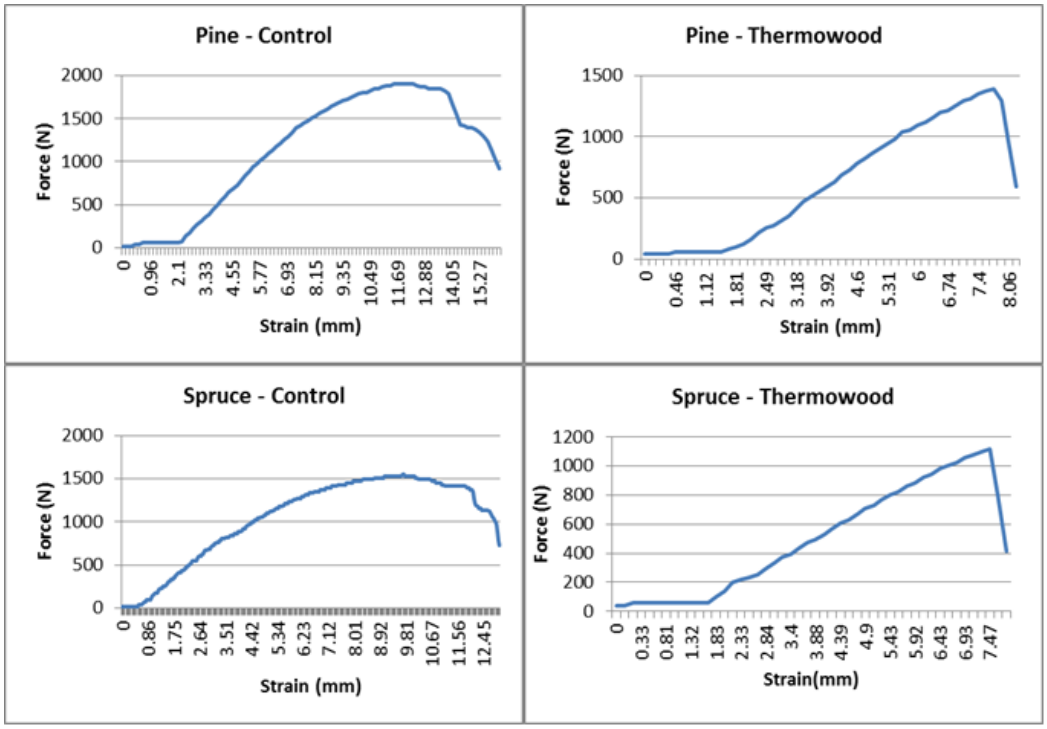

Fig. 4. Fracture behavior of heat-treated and control samples in bending

A laboratory-scale heat treatment (heating at 120, 150, and 180 °C for 2, 6, and 10 h) showed that the decreases of mechanical properties were extended with increasing temperature and duration. For example, the highest decreases, 29.41% (10-h duration) and 10.30% (2 h-duration) for CS//; 29.28% (10-h duration) and 16.45% (2-h duration) for MOR, and 40.08% (10-h duration) and 35.49% (2-h duration) for MOE, were observed at 180 °C for Uludag fir (Korkut 2008). Under the same conditions Korkut *et al.* (2008) reported a mean decrease of 14% in MOR, 29% in MOE, and 13% in CS// for 180 °C and 2 h duration in scotch pine. Yildiz *et al.* (2006) obtained a 15.4% decrease in compression strength at 200 °C and a 2-h duration time for spruce wood. Comparing laboratory-scale and industrial scale heat treatments for the same species, the oven heat treatments affect mechanical properties of wood more than industrial heat treatment. Esteves *et al.* (2008) reported similar results and indicated that the cause of this difference is possibly due to the oxidation reaction and higher hemicellulose degradation.

According to Sahin Kol (2010), the MOE was reduced by 13.1% for pine and 9.5% for fir with ThermoWood treatment. Also, she found that heat treatment caused a decrease in MOR by 59.5% and 10.5% for pine and fir, respectively. Although there was no considerable change reported for compression strength in the study, we found a considerable decrease with the same process (Table 1).

Table 1. Heat Treatment Effects on Some Properties for Pine and Spruce Wood

Tree	Properties	N	Control			ThermoWood			%
			Mean	SE	cv	Mean	SE	cv	Decrease
Pine	D0 (g/cm^3)	36	0.45	0.01	0.06	0.43	0.01	0.07	4.44
	D12 (g/cm^3)	36	0.49	0.01	0.06	0.46	0.01	0.07	6.12
	MOR (12% MC) (N/mm^2)	36	79.88	1.48	0.11	46.11	2.02	0.26	42.28
	MOE (12% MC) (N/mm^2)	36	4563.70	103.40	0.14	3572.97	96.15	0.16	21.71
	CS// (12% MC) (N/mm^2)	67	37.49	0.88	0.19	31.73	0.74	0.19	15.36
	*MOR (N/mm^2)	70	85.44$^{(1)}$	1.46$^{(1)}$	0.10$^{(1)}$	69.47$^{(3)}$	3.02$^{(3)}$	0.26$^{(3)}$	18.69
	*MOE (N/mm^2)	70	4717.53$^{(1)}$	104.89$^{(1)}$	0.13$^{(1)}$	4294.94$^{(3)}$	114.55$^{(3)}$	0.16$^{(3)}$	8.96
	*CS// (N/mm^2)	70	43.26$^{(2)}$	0.50$^{(2)}$	0.11$^{(2)}$	37.37$^{(4)}$	0.42$^{(4)}$	0.11$^{(4)}$	13.62
Spruce	D0 (g/cm^3)	40	0.39	0.01	0.14	0.38	0.01	0.16	2.56
	D12 (g/cm^3)	40	0.42	0.01	0.14	0.40	0.01	0.15	4.76
	MOR (12% MC) (N/mm^2)	40	60.69	2.30	0.24	37.93	1.80	0.29	37.50
	MOE (12% MC) (N/mm^2)	40	6011.13	465.89	0.31	5440.15	471.37	0.32	9.50
	CS// (12% MC) (N/mm^2)	80	50.16	0.84	0.22	31.60	0.47	0.13	37.00
	*MOR (N/mm^2)	75	62.41$^{(1)}$	2.16$^{(1)}$	0.22$^{(1)}$	57.32$^{(3)}$	2.64$^{(3)}$	0.28$^{(3)}$	8.16
	*MOE (N/mm^2)	75	6557.71$^{(1)}$	568.56$^{(1)}$	0.33$^{(1)}$	6087.77$^{(3)}$	465.56$^{(3)}$	0.28$^{(3)}$	7.17
	*CS// (N/mm^2)	80	34.61$^{(2)}$	0.81$^{(2)}$	0.19$^{(2)}$	25.55$^{(4)}$	0.49$^{(4)}$	0.14$^{(4)}$	26.18

*:These values represent the group of conditioned samples stored for four months in a conditioning room at 20 °C (±2 °C) and 65% (±5%) relative humidity
SE: Standard Error
cv: Coefficient of Variation
D0: Oven-Dry Density
D12: Air-Dry Density
(1) 10.2 to 10.5% MC, (2) 11.5% to 13% MC, (3) 3.5 to 3.7% MC, (4) 5.5 to 6% MC

To determine the real effects of treatment, control and treated samples should have the same moisture content. This is the reason for acclimatization at specific conditions (*i.e.*, 20 °C and 65% relative humidity) before the mechanical test and the use of conversion formulas to equalize sample moistures at a specific level (generally 12%) after tests. However, changes that occur after heat treatments are irreversible (as mentioned above) and theoretically this situation would continue. The current results support the idea that after acclimatization, heat-treated samples have almost half the moisture content of control samples. One might anticipate that heat-treated wood (ThermoWood in particular) would always have lower moisture content than untreated wood. Therefore, to have a realistic idea about strength properties and the mechanical design values of heat-treated wood in outdoor conditions, realistic moisture contents should be considered.

The color values showed clear effects of high temperature on color changes (Table 2). The negative value of lightness (ΔL^*) and chromaticity coordinates ($\Delta a^*$and Δb^*) indicated that color became darker after heat treatment. In this study, L^* values in color change tests decreased after heat treatment; on the other hand, a^* and b^* values generally increased. There was no significant difference ($p>0.05$) between the color values of radial and tangential sections (except Δb^* values of pine). According to Fengel and Wegener (1989) and Sundqvist (2002), the reason for color changes is the production of chromophores as a result of the hydrolytic reactions that occur during heat treatment. The extent of thermal degradation is directly related to the extent of the darkening of the color properties (Kawamura *et al.* 1996). However, the attained darker color after heat treatment is not stable against light exposure (Mitsui *et al.* 2003), and currently there is no cost-effective and easy method to prevent this fading (Kaygin *et al.* 2009).

Table 2. Heat Treatment Effects on Color Values for Pine and Spruce at Radial and Tangential Sections

Tree	Wood Section	Treatment	L^*	a^*	b^*	ΔL^*	Δa^*	Δb^*	ΔE^*
Pine	Radial	Control	81.64	3.55	16.51				
		TW	45.76	9.54	16.52	35.88	−5.99	−0.01	36.38
	Tangential	Control	81.23	3.53	15.78				
		TW	44.20	9.10	17.80	37.03	−5.57	−2.02	37.50
Spruce	Radial	Control	81.83	3.12	15.05				
		TW	47.40	9.03	16.56	34.43	−5.91	−1.52	34.97
	Tangential	Control	81.69	2.93	15.28				
		TW	46.56	9.01	16.64	35.13	−6.08	−1.35	35.68

CONCLUSIONS

1. The ThermoWood process caused a 2.56% (for spruce) and 4.44% (for pine) decrease in density (D0). The mass loss of heat-treated samples was 5.8% for pine and 7.6% for spruce.
2. Dimensional stability was considerably improved.

3. Color became uniformly darker after treatment for clear parts of lumbers. There was no significant ($p>0.05$) difference between the color values of radial and tangential sections (except for the Δb^* values of pine).
4. The ThermoWood process caused a significant ($p<0.05$) reduction (8% to 42%) for all investigated mechanical properties at a specified moisture level (12%). The highest decrease among all investigated strength was found for modulus of rupture. However, the mechanical properties of wood are closely related to its moisture content and heat-treated wood is less hygroscopic than untreated wood. After acclimatization under the same conditions, the moisture contents of heat-treated samples were lower than untreated ones and the mechanical test results for the actual moisture of heat-treated samples showed that the decrease (%) in strength values was lower than in samples with specified moisture (12%) content.
5. Different failure behaviors (abrupt fracture at lower forces) of heat-treated wood were observed in bending tests.
6. Comparing laboratory-scale heat treatments for the same species, the oven heat treatments affected the mechanical properties of wood more than industrial heat treatment.

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